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MEASUREMENT OF SIZE DISTRIBUTION OF DIESEL PARTICLES: EFFECTS OF INSTRUMENTS, DILUTION METHODS, AND MEASURING POSITIONS

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ABSTRACT–Size distribution of diesel particles measured by ELPI and SMPS were compared. The results of ELPI and SMPS showed acceptable agreements in the qualitative comparison but showed differences in the quantitative comparison. In addition, the results of ELPI and SMPS showed a same trend about the change of engine loads. In this study, the effects of dilution methods and measuring positions on the measurement of PM size distribution were also studied by using the SMPS. As results, the decrease of large particles and the increase of small particles were observed when the dilution air was heated. It was also observed that the number concentration of the diesel particles was varied within 20% by the different measuring positions of 140 cm.

KEY WORDS : Diesel engine, Particulate matters (PM), Size distribution, ELPI (Electrical Low Pressure Impactor), SMPS (Scanning Mobility Particle Sizer), Dilution, Measuring position

1. INTRODUCTION

In addition to PM total mass, its size distribution is recently receiving increased attention because of the noxious effect of nanoparticle to human health. According to medical researches, the fraction of particles deposited in bronchioles and pulmonary region increases with the decrease of size due to the higher mobility of small particles (Hinds, 1999 and Mayer *et al.*, 2001).

Diesel particles are composed of volatile and nonvolatile particles. The volatile particles in the nanoparticle range, $D_p < 50$ nm, are usually formed from hydrocarbons and sulfur compounds during dilution and cooling processes. On the other hand, nonvolatile particles in the accumulation mode range, 50 nm $< D_p <$ 1 μm, are generated in a diesel engine at the early stage of combustion. As the exhaust gas cools, the condensable species such as hydrocarbon, sulfuric acid and water can be absorbed on the surfaces of the agglomerates (Kittelson, 1998). Kwon *et al.* (2003) studied the size-dependent volatility of the diesel particles in a diameter range of 30–70 nm. They observed that the pattern of size distribution changed from single mode size distribution to bimodal distribution with high temperature of a heater. Burtscher *et al.* (2001a) studied the separation of the volatile and nonvolatile components using a thermodesorption method.

ELPI and SMPS have been widely used to measure the size distribution of particles in a variety of applications (Tsukamoto *et al.*, 2000; Li *et al.*, 1993). The ELPI using cascade impactors measures the particles in the size range of 30 nm–10 μm in real time. But regular cleaning of the impactors and low resolution restricted by 12 size channels are the disadvantages of the ELPI. The SMPS using an electrical mobility detection technique measures with high resolution, but it isn't suitable for the measurement of rapidly changing particles like those generated during transient engine test cycles. Marjamaki *et al.* (2000) evaluated the performance of the ELPI using monodisperse aerosols. They determined particle cut sizes of the cascade impactor and charging efficiency of the charger and compared the size distributions measured by using ELPI and SMPS. Gulijk *et al.* (2003) studied non-ideal behavior of ELPI and showed good measurements for size distributions of diesel particles using oil-soaked sintered impactor stages. Khalek *et al.* (2003) showed that the decrease of nanoparticles in the ultra-low sulfur fuel compared to the conventional fuel with

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high sulfur content, which was measured by using ELPI. Kwon *et al.* (1999) showed the effect of diesel oxidation catalysts and diesel particulate traps on the particle number concentration in a diesel engine using SMPS.

The size distribution of diesel particles can be measured differently by different instruments because they use different principles for classifying the particles by size. The measurements can be also influenced by sampling techniques. This study is conducted to clear the effects of instrument, dilution ratio, and measuring position on the size distribution of diesel particles.

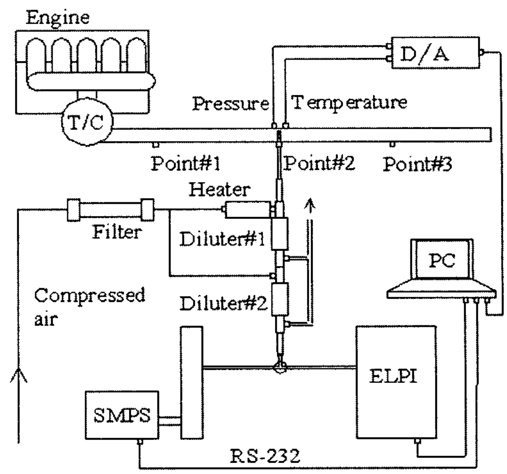
2. EXPERIMENTAL SETUP

A schematic diagram of the experimental setup used in this study is shown in Figure 1. It is composed of an diesel engine, a diluter system, ELPI and SMPS. Table 1 presents the specifications of the test engine.

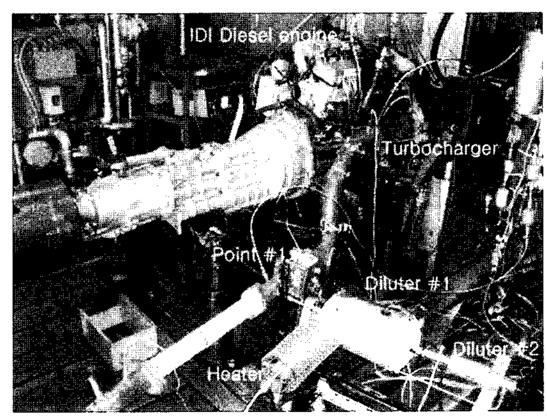
In our study, an ELPI manufactured by Dekati Ltd. is used. The ELPI has 12 stages and measuring size range is from 30 nm to 10 μm. Diesel particles are first charged electrically in a charger and the particles discharge currents when they are trapped on a plate of an impactor. By measuring these currents and applying charging efficiency for each particle size, the number of diesel particles are determined. The advantage of ELPI is short measurement time but it cannot measure particles smaller than 30 nm and suffered from impactor fouling. Impactor stages coated with Apiezon-L grease is used to prevent rebounding the particles.

The SMPS, manufactured by Grimm, consists of an electrostatic classifier (EC) and a condensation particle counter (CPC). Measuring range of the SMPS is from 10 nm to 875 nm with high resolution of 255 channels, but scanning time is relatively slow as 405 seconds for one measurement. The principle of EC lies in the direct proportionality between the velocity of a charged particle in an electric field and size of the particle. As an aerosol enters the CPC, it is saturated with alcohol vapor while it passes over a heated pool of alcohol. The vapor saturated particles then flow into a condenser, where the alcohol condenses onto the particles. The enlarged particles are counted by a light scattering technique. SMPS measurements cover wide range of nano-size diesel particles but the measurement time is too long to test for transient engine operation.

Before measurement, the exhaust gas was diluted using two ejector type diluters manufactured by Dekati Ltd. In the diluter, the high flow rate of the dilution air induces a pressure drop in the ejector nozzle causing sample flow into the diluter. Heated dilution air was supplied into the first diluter to prevent condensation of volatile component in the exhaust gas, and unheated



(a) Schematic diagram



(b) Experimental setup

Figure 1. An experimental setup for measuring the size distribution of diesel particles.

Table 1. Engine specifications.

Displacement	2974 cm^3
No. of cylinder	5
Bore × Stroke	89 × 92.4 mm
Compression ratio	22:1
Maximum torque	23.4 kgf-m @ 2400 rpm
Type	4 stroke Indirect injection Water cooled

dilution air was supplied into the second diluter. Since a dilution ratio was varied with the inlet pressure of a diluter, the pressure was measured with piezo-type pressure sensor. The compressed air filtered off water and oil components was delivered with pressure of 2 bar for dilution of the exhaust gas.

3. RESULTS AND DISCUSSION

3.1. Comparison between ELPI and SMPS

Figure 2 shows the repeatability of ELPI measurement. The size distribution was measured four times with a 7 minute interval during idle engine operation. Figure 2(a) shows the size distributions of all measurements, and relative standard deviations of the measurements are presented in Figure 2(b). Here, relative standard deviation refers to a percent value of a standard deviation divided by a mean value. The greatest relative standard deviation is 21% at the first stage detecting the smallest size particles, but stable measurement is obtained in the other stages with relative standard deviations of 2–12%.

In order to check the performance of ELPI in a long time measurement, currents detected in the impactor stages are observed in Figure 3. The experiment was performed for 45 minutes at idle condition. The current of the first stage decreases with time and those of the 4–6th impactors increase slightly. It seems that the main reasons of this result are the particle overloading on the surface of impactor or fouling of the charger. This result is the same as the measurements conducted by Gulijk *et al.* (2003).

The repeatability of SMPS measurement of idle condition is shown in Figure 4. Figure 4(a) presents the size distribution of all measurements, and the relative standard deviations are shown in Figure 4(b). It shows that the measurements of 20 nm–300 nm particles are

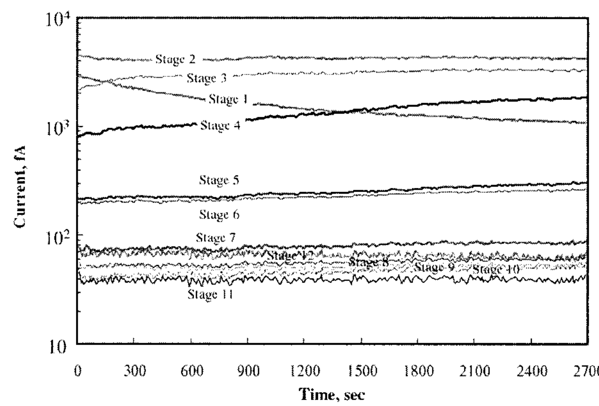
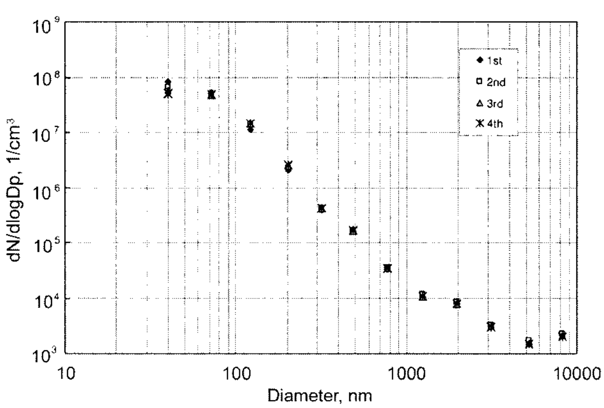
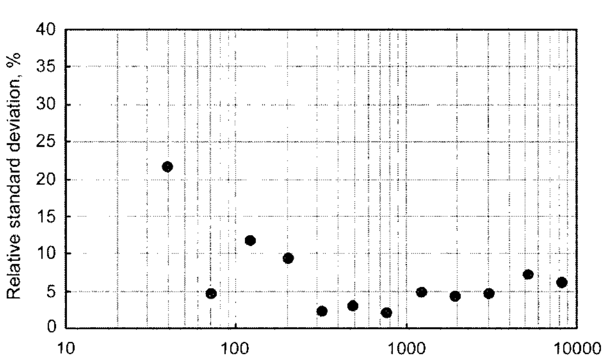


Figure 3. Time series variation of currents detected by impactor stage during idle engine operation.

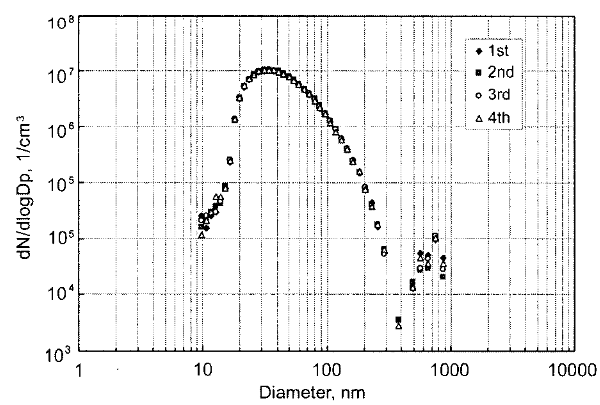


(a) Size distribution

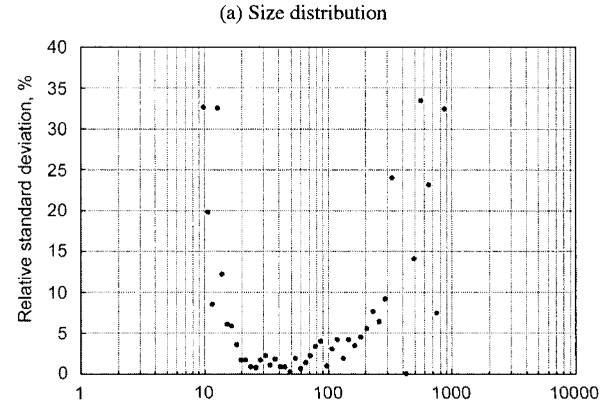


(b) Relative standard deviation

Figure 2. Repeatability of ELPI measurements during the idle engine operation.



(a) Size distribution



(b) Relative standard deviation

Figure 4. Repeatability of SMPS measurement during idle engine operation.

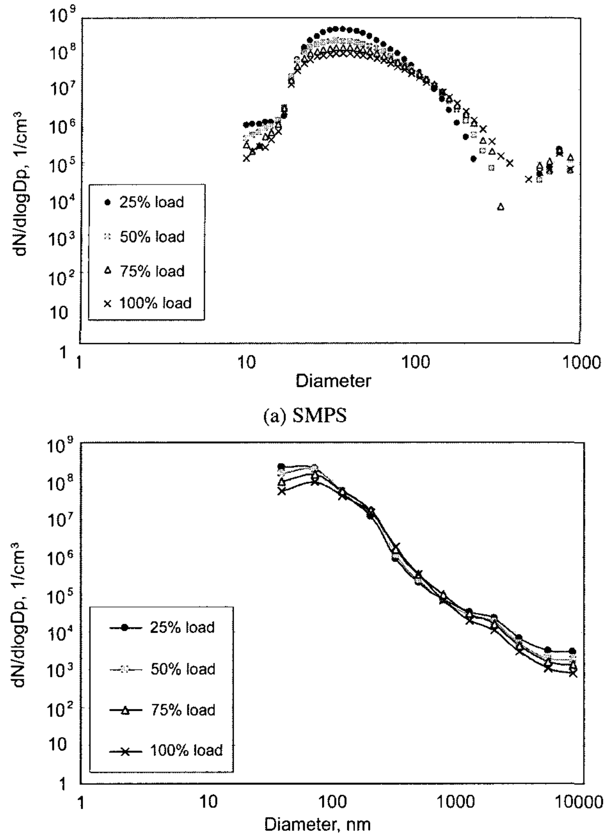


Figure 5. Size distribution of diesel particles with respect to engine load conditions at 1600 rpm.

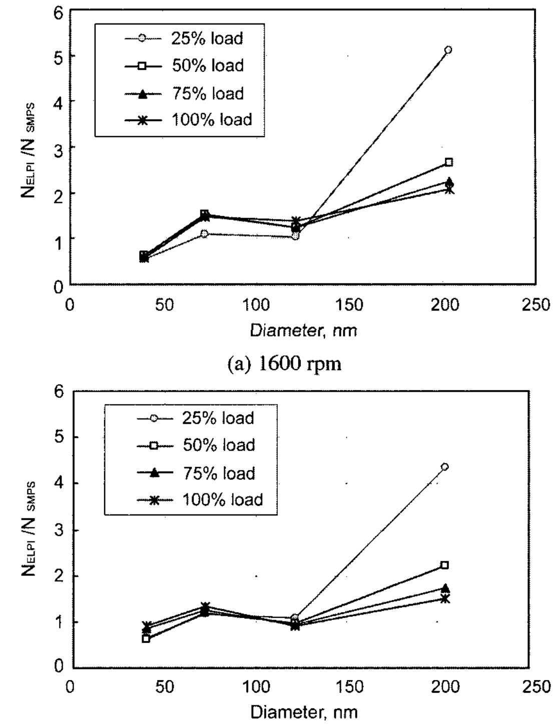


Figure 6. Ratio of particle number concentration measured by ELPI to that of SMPS.

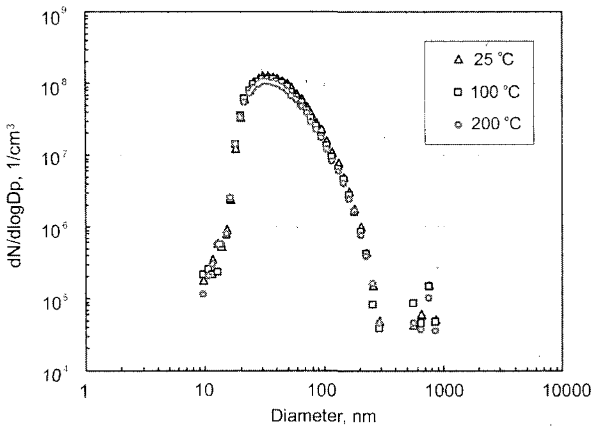
stable, but the measurements below 20 nm and over 300 nm are relatively unstable.

In Figure 5, size distribution with different engine loads at 1600 rpm is shown. Figure 5(a), which is measured by SMPS, shows that the number concentration of particles below 120 nm decreases whereas that of 120 nm–300 nm increases according to the increase of engine load. For particles of diameter above 300 nm, there is no trend with engine load. Figure 5(b) shows the results measured by ELPI. The result of ELPI is similar to that of SMPS. The number concentration of particles below about 100 nm decreases whereas that of 100–400 nm increases according to the increase of engine load. For particles of diameter above 400 nm, there is no trend. But the effect of engine loads on size distribution is less clear in ELPI than in SMPS due to low resolution.

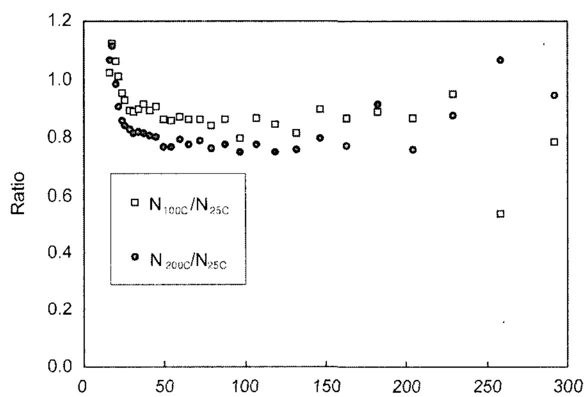
Figure 6 shows the particle number concentration ratio of ELPI to SMPS. Since ELPI and SMPS have different size resolutions, the measured value of ELPI is divided by interpolated value of SMPS. Figure 6(a) is the results for 1600 rpm. Number concentrations of ELPI for the particles above 40 nm are greater than that of SMPS. It is also shown that the differences between the results of two instruments are greater in the large size particles than in the small size particles. ELPI uses an aerodynamic mechanism to classify the particles by size, but SMPS uses electrical mobility. Such a different principle of instrument leads to different results. Burtscher (2001b) explained that these differences might come from unknown density and nonspherical structure of diesel particles. Figure 6(b) shows the results for 2400 rpm. It shows the similar results with Figure 6(a). The difference between the results of ELPI and SMPS is greater in the larger size particles.

3.2. Effect of Dilution Air Temperature

To investigate the effect of dilution air temperature on the size distribution, the first dilution air was heated from 25°C to 100°C and 200°C, while unheated dilution air was supplied into the second diluter. Figure 7(a) shows the change of size distribution with the different dilution air temperatures. Figure 7(b) shows the ratios of particle number concentration, in which the particle number concentration of 100°C or 200°C is divided by that of 25°C. About 20% of particles in the diameter above 20 nm are reduced with the heated dilution air from 25°C to 200°C, but the number concentration of particles in the

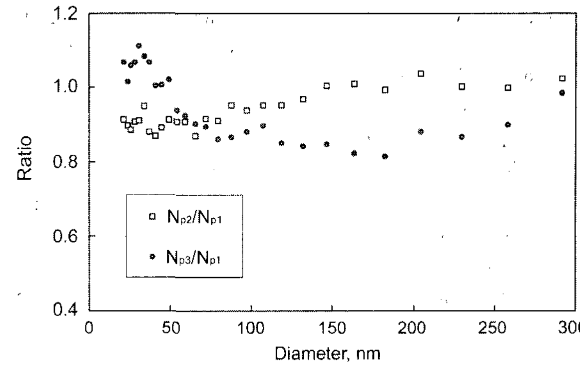


(a) Size distribution

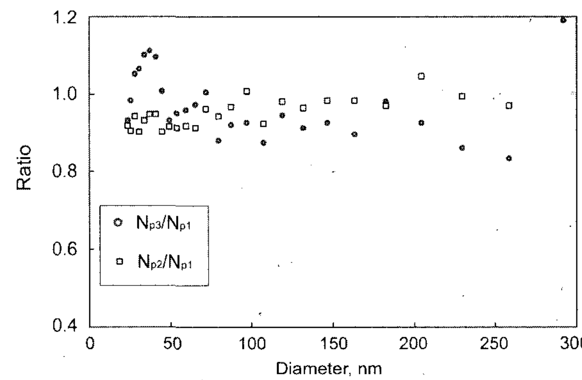


(b) The ratio of number concentration

Figure 7. Effect of dilution air temperature on the number concentration at idle condition.



(a) 1600 rpm full load



(b) Idle

Figure 8. The effect of measuring position on the number concentration.

diameter bellow 20 nm increases. It means that large diesel particles are shifted to the small size particles by evaporation of the volatile components in high temperature.

3.3. Effect of Measuring Position

The size distribution was measured at three different positions on an exhaust pipe. The first measuring position (#1) was located at the downstream of 100 cm from a turbocharger and the second (#2) and third (#3) positions were located at the downstream of 70 cm from the first and second position, respectively. The ratio shown in Figure 8 is the value of particle number concentration at position #2 and #3 divided by that of position #1. In Figure 8(a), the results of a full load condition at 1600 rpm, the particle number concentration below the size of 150 nm is reduced at position #2 compared with position #1. More remarkable change is observed at the position #3. The particle number concentration above the size of 50 nm is reduced at position #3 compared with position #1, but the number concentration below 50 nm increases. Figure 8(b), the results obtained from idle condition, shows the similar results with Figure 8(a). The above results suggest that the number concentration of the diesel particles can be varied 20% with different measuring positions of 140 cm because of the collision between particles and condensation of volatile components and water.

4. CONCLUSIONS

The size distribution of particles emitted from an indirect injection diesel engine was measured by using ELPI and SMPS. Performance of the two instruments were compared and the effect of dilution method and measuring position were investigated. From this study, the following conclusions were achieved.

(1) Stable results were obtained by both SMPS and ELPI in the repeated measurements during idle engine condition. The measurements of ELPI and SMPS showed a same trend about the change of engine load.

(2) From the comparison between ELPI and SMPS for size distribution of the diesel particles, a qualitatively

acceptable similarity was obtained but quantitative comparison was difficult. The difference between the results of ELPI and SMPS was greater in the larger size particles.

(3) The large diesel particles decreased and the small particles increased with the heated dilution air. About 20% of particle number varied by the temperature difference of 25°C–200°C of dilution air.

(4) The number concentration of the diesel particles varied 20% with different measuring positions of 140 cm.

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